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Abstract. This paper reviews the physics and applications of Normal-Insulator-Superconductor (NIS) tunnel junctions. The current-voltage properties of NIS junctions are diode-like with a strong temperature dependence. Hence, these structures can be used as sensitive thermometers at temperatures well below the energy gap, Δ, of the superconducting electrode. For junction voltages comparable to Δ/q, current flow removes energy from the normal electrode. This property has been exploited to build refrigerators capable of cooling thin-film circuits from 0.3 K to 0.1 K. Calorimeters and bolometers for the detection of X-rays and millimeter-wave radiation, respectively, have successfully been built from NIS junctions. NIS junctions have also been used to probe the superconducting state. Finally, recent ideas for the use of NIS junctions as simple circuit elements are described.

INTRODUCTION

Electron tunneling in Normal-Insulator-Superconductor (NIS) junctions was first observed by Giaever in 1960. [1] The current-voltage characteristics of NIS and SIS junctions provided a direct measurement of the superconducting density-of-states and energy gap, Δ, as functions of material, magnetic field, and temperature. Tunneling experiments with these junctions were also a direct and very successful test of the 1957 Bardeen, Cooper, and Schrieffer theory of superconductivity. Giaever shared the 1973 Nobel prize for his work on electron tunneling in superconductors.

Technologically, NIS junctions have changed little after 40 years of experimentation. Usually, they consist of two thin films separated by an insulating layer a few nanometers thick. The most commonly used insulator is Al_2O_3 because a barrier free of pin-holes is easily fabricated by the exposure of Al to oxygen.

The current-voltage properties of a NIS junction are diode-like with the upturn in current occurring at voltages V near Δ/q. At voltages much larger than Δ/q, the junction behaves likes a resistor with value R_n. The thickness and quality of the insulating barrier can be described by the specific resistance, R_{sp}, which is the product of the junction area A and R_n. Typical values of R_{sp} are 500 $\Omega\mu m^2$ or more. The resistance at voltages near zero, sometimes called the dynamic resistance R_{dyn}, exceeds R_n due to the absence of electronic states within the energy gap. In high-quality junctions R_{dyn}/R_n can be 10^3 or more.

For voltages below Δ/q, the current through a NIS junction can be approximated by

$$I \approx \frac{\Delta}{2qR_n}\sqrt{\frac{2\pi k_b T}{\Delta}}\, e^{\left(\frac{qV-\Delta}{k_b T}\right)} \qquad (1)$$

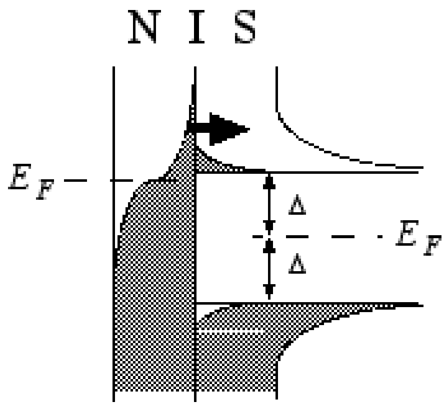
where T is the electron temperature in the normal electrode. [2] It can readily be seen that current flow at these voltages is exponentially activated with T. This temperature sensitivity is exploited in a number of the devices described later in this paper. The temperature derivatives are given by $dI/dT = (1/2 + \phi)\, I/T$ and $dV/dT = -(1/2 + \phi)\, k_b/q \approx -(1/2 + \phi)(0.1\ \mu V/mK)$, respectively, where ϕ is $(\Delta - qV)/k_bT$. These expressions are often useful for making simple estimates of device behavior.

NIS REFRIGERATORS

For bias voltages slightly smaller than Δ/q, the electrons which tunnel through a NIS junction are drawn from the hot tip of the Fermi distribution in the normal electrode as shown in figure 1. Hence, current flow through the junction cools the normal electrode and the cooling power P_{cool} is given approximately by $I(\Delta/q - V)$. [3] A much larger power equal to $IV + P_{cool}$ is dissipated in the superconducting electrode due to the creation of quasiparticles. Efforts are ongoing to build refrigerators for thin-film focal plane elements based on this cooling. The cooling power of a junction is reduced when the electronic system of the superconducting electrode is hotter than that of the normal metal; this effect sets a lower limit on the base temperature that can be achieved from a given bath temperature. [4]

In practice, the base temperature of a NIS refrigerator is limited by the power load from the environment which can usually be expressed as $P_{env} = K(T_{env}^n - T^n)$ where K and n are geometry-dependent constants. In the first demonstration of NIS refrigeration, only the electrons of the normal metal were cooled. [3] For electron cooling, n is 5, K is $\sum V$ where $\sum$ is the electron-phonon coupling constant $\approx 2\ nW/\mu m^3K^5$, and V is the volume of the normal electrode. A useful improvement was the introduction of a SINIS structure in which the central normal metal was refrigerated by two junctions biased in series. [5] In this geometry, tunneling through one junction removes hot electrons and tunneling through the other fills hot holes. Electron cooling from 0.3 to 0.1 K was achieved in these devices which is very close to the achievable optimum. The junction areas and normal metal volume in these devices were roughly 1 μm^2 and .05 μm^3, respectively.

The most attractive application of NIS refrigerators is the cooling of thin-film focal plane elements such as transition-edge sensors (TESs). To cool a detector which is electrically separate from the refrigerator, the refrigerator and detector need to be co-located on a thermally isolated structure such as a suspended membrane. In this geometry, tunneling through the NIS junction successively cools the electrons of the normal electrode, the lattice of the normal electrode, the lattice of the isolated structure, the lattice of the detector, and the electrons of the detector. The closest realization to date of a complete NIS refrigerator is shown in figure 2.



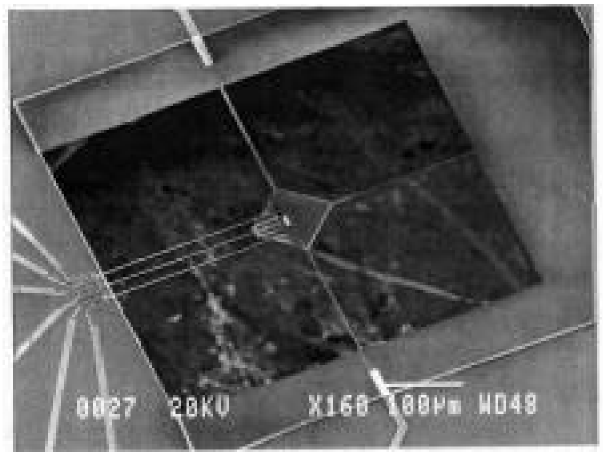


FIGURE 1. Energy-level diagram of a NIS junction. Occupied electron states are shaded. **2.** SEM micrograph of a NIS refrigerator. [6] The suspended island in the center is cooled from 0.2 to 0.1 K by many NIS junctions located on the substrate at the left side of the figure.

The IV power dissipated in quasiparticle creation becomes increasingly important in large area junctions and junctions suspended on membranes. In large junctions, the quasiparticle density in the superconducting electrode is higher because quasiparticles must diffuse farther to exit the junction region. The accumulation of quasiparticles in the superconductor degrades device performance in two ways. First, the cooling power is reduced by a process called back-tunneling in which electrons from below the Fermi level of the normal metal tunnel to fill hole-like quasiparticle states in the superconductor. [4, 7] Second, phonons from recombining quasiparticles can enter and heat the normal electrode. In suspended junctions, phonons cannot easily escape into the substrate and are readily captured by the large heat capacity of the normal electrode.

A number of techniques exist to prevent the return of IV power to the normal electrode. The quasiparticle density in the superconducting electrode can be lowered by using a thick or defect-free film. The overlap between the normal and superconducting electrodes can be made wide but shallow, or many small junctions can be used. In devices using a suspended membrane, the junction can be located off the membrane and the normal electrode can be extended onto the membrane as a cold finger. One of the most powerful techniques is borrowed from detector physics: the use of a normal metal film to trap quasiparticles present in the superconductor. [8] The normal trap acts as a quasiparticle sink and its electrons capture almost all of the quasiparticle energy.

A potential application of NIS refrigerators is the cooling of small numbers of thin-film sensors from 0.3 to 0.1 K for use in X-ray microanalysis. A NIS stage could allow a pumped ^{3}He refrigerator to be used in place of a more complex and more expensive demagnetization or dilution refrigerator. The power dissipated by a TES is about 5 pW. An aluminum junction that cools from 0.3 to 0.1 K subject to electron-phonon loading has, very roughly, 0.2 pW/μm^2 of excess cooling power. Hence, junction areas of a few 10s of μm^2 are required. Electron cooling from 0.3 to 0.1 K was recently achieved with traps directly underneath 30 μm^2 junctions. [9] A proposed approach for achieving cooling in junctions with dimensions of 10^3-10^4 μm^2

is to combine the substrate and superconducting electrode in a large-volume, high-purity superconducting crystal. [10] Another recent development is refrigeration by tunneling through the Schottky barrier in semiconductor-normal junctions. [9]

NIS DETECTORS

In detectors built from NIS junctions, an external stimulus is coupled to the normal electrode. A temperature change ΔT in the normal electrode produces a current or voltage response ΔT (dI/dT) or ΔT (dV/dT). NIS detectors have been used to measure X-rays, ions, and millimeter-waves.

NIS X-ray detectors operating near 100 mK have achieved energy resolutions of 22 eV at 6 keV with an absorbing area of 10^{-2} mm^2 [11] and 30 eV at 6 keV with an area of 0.25 mm^2. [12] The absorber was thermally linked to the normal electrode of the junction. The absorber was positioned on a dielectric membrane while the junction was positioned on the adjoining substrate. The junction area was about 4 ¥10^4 μm^2 and current pulses were recorded by a SQUID amplifier. The detector response time was given by $C/(G_o + G_{NIS}) \approx 20$ μs where C is the device heat capacity and G_o and $G_{NIS} = dP_{cool}/dT$ are the intrinsic and junction thermal conductances. The theoretical energy resolution ΔE_{FWHM} is 2.6 $(k_b T^2 C)^{1/2}$ $(1.4 + 0.4\ G_o\ /\ G_{NIS})^{1/2}$. [11] The resolution is best when $G_{NIS} >> G_o$ so that photon energy is carried out of the device by electrons tunneling through the junction. This condition is analogous to achieving refrigeration and is therefore difficult to meet in large junctions. Self-heating in a junction reduces the X-ray signal and adds noise. The optimal resolution is 1.3 ¥ 2.35 $(k_b T^2 C)^{1/2}$. In contrast, the optimal resolution for a TES device is $2.4/\alpha^{1/2}$ ¥ 2.35 $(k_b T^2 C)^{1/2}$ where α = (T/R) (dR/dT) can exceed 100. [13] While difficult to realize, a NIS detector that self-cools would have an improved signal-to-noise ratio due to the low internal temperature. [14]

NIS devices designed for X-ray detection have also been used to measure the kinetic energy and arrival time of biomolecular ions. [15] The speed, size, and resistance to saturation of NIS devices can be well matched to some ion detection applications.

Millimeter-wave bolometers have been built in which radiation is antennae-coupled to a normal metal film which is also the normal electrode of a NIS junction. [16] The sensitivity of these devices is in part derived from the extremely small volume, approximately 0.1 μm^3, of the normal metal. The power responsivity, S = dV/dP, of these devices is given by (dV/dT) G^{-1} $(1 + \omega^2\tau^2)^{-1/2}$ where $\tau = C/G \approx 20$ μs and G = volume ¥ 5∑T^4 is set by electron-phonon coupling. At 0.1 K, the responsivity to electrical heating has been measured to be 1-4 ¥ 10^9 V/W. [16, 17] So far, the dominant noise source has been the input noise of the read-out voltage amplifier. If the input noise of this amplifier is 1 nV/$Hz^{1/2}$ and S is 10^9 V/W, the noise-equivalent-power will be 10^{-18} W/$Hz^{1/2}$. Because of their sub-micron size, it may be possible for the junctions in these devices to self-cool. Self-cooling and the resistance of NIS devices to saturation are attractive for millimeter-wave applications in which the signal rides on top of a much larger background power. Detailed calculations of bolometer performance in different operating regimes are given in [18].

NIS JUNCTIONS AS PHYSICS TOOLS

NIS junctions have two useful properties for studying quasiparticle behavior. First, they can create a quasiparticle population whose size and energy are well understood. A current I through a NIS junction creates quasiparticles in the superconducting electrode at a rate $I/q - \Gamma_{bt}$. [7] The term Γ_{bt} is the back-tunneling rate. This term can often be neglected but is important when a large quasiparticle population is present in the superconductor. The average energy of the injected quasiparticles can be calculated from the junction voltage and temperature. [19] The second useful property of NIS junctions is their ability to act as on-chip power meters. When heater leads are coupled to the normal electrode, it is possible to calibrate the junction response to some stimulus against known levels of Joule power.

NIS junctions were used to measure the energy that a quasiparticle trapped in a normal metal deposits in the electronic system of the trap. [20] Quasiparticles were injected into a superconductor by one junction and the heating of an adjoining normal metal trap was measured with another junction. Trapped quasiparticles were observed to transfer more than 80% of their energy to the electrons of the trap. The same structure was used to make the first observations of the energy-dependent quasiparticle group-velocity. [19] When the injection voltage and temperature were varied `to increase the average quasiparticle energy, the fraction of quasiparticles reaching the trap was observed to change in a manner that was well-explained by a higher diffusion constant and, consequently, fewer recombination losses.

NIS CIRCUIT ELEMENTS

Two recent ideas for circuit elements based on NIS junctions are briefly discussed. A NIS junction can act as a current-controlled variable resistor. Integrated into a bias network, the junction provides high isolation when a line is quiescent and low power dissipation when the same line is addressed. [21]

The second idea is a superconducting three-terminal device called the Quasiparticle Trapping Transistor (QTT) built from two NIS junctions connected in series. [22] Quasiparticles injected into the superconducting electrode of the first junction are trapped in the normal electrode of the second. Current gain is realized in this structure because of the efficiency of quasiparticle trapping into a normal metal: each trapped quasiparticle deposits an energy close to Δ, thereby enabling up to Δ/k_bT electrons to tunnel through the second junction. The response time of the device is given by the heat capacity of the trap divided by its thermal conductance to the outside world, which is set by electron-phonon coupling, the acoustic-mismatch at the film-substrate interface, or the cooling power of the second junction. The QTT may be able to act as an on-chip amplifier for other low temperature detectors, or as an integrated detector-amplifier. Recently, a QTT operated at 4.2 K has produced values of differential current gain, dI_{out}/dI_{in}, as high as 80. [23]

CONCLUSIONS

This paper has summarized the basic physics of NIS junctions as well as efforts to apply them as refrigerators, detectors, physics tools, and circuit elements. Certain threads connect device behavior in these widely varying applications. Most of the device concepts exploit the temperature sensitivity of the NIS current-voltage curve. More subtly, the accumulation of quasiparticles in the superconducting electrode degrades both NIS refrigerator and detector performance. Electron tunneling from below the Fermi level of the normal metal not only limits refrigerator performance, it also accounts for deviations from I/q in the quasiparticle injection rate. The trapping of quasiparticles into a normal metal has been used very successfully to reduce self-heating in both NIS X-ray detectors and refrigerators. At the same time, NIS junctions have been used to study the energy balance during trapping and trapping provides the gain mechanism of the QTT.

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